Optimization of a Transmission Network

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1 Introduction

U.S. Defense Agency, D.A.R.P.A. has recently issued a tender called C.O.R.O.N.E.T , for it's next generation core network environment. The RFQ contains strict requirements for the transmissionation network , and will pave the way for the new technologies to be deployed in ten years timeframe in the U.S, and perhaps 12-15 years in Europe. The requirements are strict in terms of bandwidth, reliability, scalability and network quality of service providing capabilities. Building up such a network with today's technology would be extremely challenging, and is far and away from real world scenario, where technology, resources, and several other constraints limit the possibilities. Two well defined paths lead to such an advanced network –

1. good definition of backbone network requirements, and forward-looking architecture design,
2. leveraging present resources as long as it can be done.

The following paper will describe the second option how to leverage and design, based on a scientific basis, and will show the findings of a real-life optical transmission network audit and redesign project.

The paper discusses a transmission network optimization project, first in Chapter 2 generally describing one suggested way of handling a network optimization project in general. Chapter 3 focuses on the characteristics of a Transmission network optimization – as a subclass of network optimizations. Chapter 4 discusses certain mathematical background used for reaching practical results. Chapter 5 describes one practical example, and the results reached. The paper is organized in a way that it starts with a general overview, then goes into more details, and finally shows one practical example. In Chapter 6 we give a brief summary of the paper.

2 Phases of a network optimization project

A network optimization is a general term. The process itself can have a number of different meaning depending on the network environment, and the goal of project. Without going into details (because [1] is entirely dedicated to optimization of networks), a few cases will be listed up in order to show its complexity.

The term network itself can be different depending on its type: eg. it can be transportation network, a telecommunication network or network model of a phenomenon, or device. Each have its on characteristics, in this chapter we are focusing on telecommunication networks in general.

Telecommunication networks can also be very different depending on the technology being used. From Chapter 4 the paper will focus on a subclass of telecommunication networks, namely traffic demand optimization of transmission networks. In this Chapter, we are focusing on the common characteristics of Telecommunication network optimization.

Not only the term network, but the term optimization can mean a number of things,, depending on the goal of the optimization, and the optimization environment. Greenfield optimizations differ greatly from optimization of an existing network, and the parameter (eg. network parameter as link capacity, delay etc.) to be optimized greatly influence the end result and the methods to be used. Further in this chapter we will focus mainly on optimization of an existing network, and the main parameter to be optimized is link capacity.

To make the paper more understandable we would like to remark the following terminology related things: further in this paper I will use need or needs as customer requirements, and demands as traffic demands between two points.

A network optimization project contains several phases – either stated in the project specification, or contains these parts as logical steps of the optimization. These phases are common in most network optimization projects.

2.1 Phase I – Defining the requirements

In the first phase of a network optimization project we need to find out the following:

- what the objective of the project is
- what the required input information should be

These have to be stated as clearly as possible, as the goal is to build up a model based on the information we received.

So the first phase of a network optimization project is finding out what the current needs are. This can be done by making a survey of current and future needs.

The survey starts with an informal understanding of problem. So that it can work efficiently a workgroup (of team members) needs to be set up, and the following topics are to be discussed:

1. The purpose of the project – this has a huge impact on the whole process. This defines what to optimize the project for – eg. the aim of the project
2. Current and/or future needs : the discussion within the workgroup has to cover what the current needs are, the possible future needs as well as the important perspectives and characteristics of the demands
3. Introducing characteristics of the topology: this should cover what the main characteristics of the topology, eg. what sort of network and traffic type is being discussed (IP/Transmission

Network/Circuit switched network/ATM/MPLS), and those characteristics that are the specific nature of the topology (Tree networks / rings/meshed networks)

4. Additional needs regarding QoS : Different traffic profiles need to be defined in this case in the network, and there specific QoS needs: this highly effects the classification
5. Protection mechanisms to be used: it has to be addressed clearly, what sort of protection mechanisms are to be used and for which traffic flows/demands should these protection mechanisms used

The result of this survey and discussions need to be put into a formal document – eg. Customer Requirements Document. Further in this document the required data from the customer need to be specified.

These are only the most important aspects that have to be covered in the first phases of the discussion. Besides these many other important questions can be discussed eg. characteristics of traffic types, special customer requests regarding nodes, traffic demands and so on.

After the defining the aim of the project, and clarifying the current requirements a snapshot of the network is needed. This can be achieved a number of ways – if there is an inventory management system available, the most obvious idea is to take a snapshot of the actual status of the inventory management system. This will form the basis of the next Phase. In case of a green-field deployment, there is no current network – so there is nothing to take a snapshot of.

2.2 Phase II – Feasibility study

The main purpose of this Phase is to find out, whether it worth making a network optimization, or the network is in a state that efforts spent on optimization (and possible commission of the optimized network) will overweight the benefits. This is more of a business benefit which is worth taking a look at. This Phase might not be needed, in case there is a clear decision that the optimization is needed.

At the beginning phase the topology of the network should be clearly visible – with all its pros and cons. From the data acquired, after preprocessing probably it turns out that some optimization parameters are far from the optimum . This have a number of reasons, most important of which is that the demands are changing over a certain time period, and a solution being appropriate in a certain stage of network development, might seem awkward or improper in a latter stage.

Of course, these assumptions can not form the basis of feasibility study – a very rough search for optimization must be done in this Phase, in order to be in a position to clearly state how much benefit an optimization can bring to the network. The result of such a rough estimation can by no means be the optimal network structure – it is to be reached in the next Phase, but it must be good enough to be able to make an effort estimation / how much benefit can the optimization bring. We have to select some criteria, that will form the basis of our study –

a. it has to show approximately how far the network parameter to be optimized is from the optimum,
b. from this criteria we need to be able to estimate the efforts required to fulfill the optimization and rerouting phases – eg. the following phases.

Selection of such criteria is to be covered in Chapter 5.

2.3 Phase III Optimization

Using a scientific approach for finding an optimum is necessary, because the optimization problem is too complex once the network size has reached a certain limit (10xn nodes+), and the problem has further constraints. This problem will be described further in Methods for transmission network *optimization*. This is the main purpose of the Optimization phase.

The purpose of this Phase is to do the actual optimization, eg. to find a reconfiguration of the network close to an optimum, that is acceptable. The optimization itself is usually a very complex problem – depending on the network type and objective of the optimization it can be an NP – complete problem. The effectiveness of the network optimization highly depends on a number of factors – number of nodes, edges, and demands in the network, as well as the requirements. Before this Phase, a new snapshot of the network is needed – which will form the basis of the optimization, because there could be several changes since the previous snapshot in a real life network.The reason for this step is that significant amount of time might have passed between the previous phase, and this phase.

Finding the optimum method for developing the optimum includes theoretical research, development of algorithms, testing, and actual running of the algorithm itself. Due to the long-lasting nature of finding, or developing a method for finding the optimum it is important to develop a method for the project that is repeatable.

It is important to note that – during the time of the actual optimization – the network itself is subject to change, so what actually will be optimized is a different network to what the network is at the end of the network. The change (whether it is change in topology or traffic demand, or any relevant network parameter)in most cases is not so significant, but it is important to note. If it is a factor to count with , therefore it is important that after the initial development of an optimum finding algorithm, using the optimum on a slightly modified traffic demand matrix should not take significant amount of time

At this Phase in order to be able to find the correct mathematical model for the optimization the following criteria should be met:

1. Topology of the network has to be available

2. Traffic demands must be available
3. Objective function must be selected

These are the preliminary requirements for finding a good mathematical representation of the network – that can form the basis of the optimization. The optimization model is also highly dependent on the purpose of the project, eg. in our understanding, what would be an optimal network(objective). Different models are being used for topology optimization or traffic demand optimization, or any other optimization problem. The different models are well described eg. in [1].

The mathematical model used for such an optimization will be discussed in *Methods for transmission network optimization*..

2.4 Phase IV Commissioning the changes

The whole purpose of network optimization is to reach an optimum state of network parameter(s) but a very important aspect should not be forgotten. After the network optimization there will be an optimal network available – on paper, or on computer, but not in the real network. Depending on the complexity and amount of work of commissioning the changes in the network, commissioning work itself could be a very important part of a Network optimization project. In certain cases, the amount of commissioning work, after doing a optimization of the network, will be so much that

1. Will never be done (in case Phase II is done well, this should not happen because in Phase II a good estimation is given for optimum, and the efforts)
2. must be done automatically somehow because the manual commissioning is such a tedious work – and manually could take too much time and effort.

2.5 Phase V – Conclusions

After the optimization is done, a very important Phase has to be done: the result must be evaluated. Questions to be answered are: is the result is according to what was expected. Should the process be made a regular process, if so how often is to be repeated. What conditions should occur to do a network optimization project once more (if not done regularly).

3 Transmission network traffic optimization

Transmission network optimization is subclass of network optimizations. The general phases of such a project have been covered in the previous chapter. In this chapter, the specific characteristics of a traffic demands optimization are covered.

Transmission network providers often reach a state of the network after few years of service, when they figure out that the current state of the network – due to the network evolution over the years – is far from being the optimum. Network owners are sometimes aware of this fact but they do not know, how much effort would be required to rearrange the network.

3.1 Characteristics of the transmission network optimization project

As the title implies, the current section deals with the *optimization* of existing network link capacities. This is an important characteristic of the problem because it means that there are *capacity constraints* on the network, imposed by current network resources (more on this in Methods for transmission network optimization), which must be taken into account in the mathematical model. This is one important characteristic of such a problem.

The second important characteristic of the project is that the optimization is a link capacity optimization task. Demands are given as certain traffic between the nodes, and the optimum routing is to be found in the network, given there are certain link capacities as constraints. The link capacities are modular.

Third important characteristic is that this is a *transmission network* with its network topology and all the characteristics for protection and quality characteristics. It is important, that protection and quality requirements must be discussed. (Only one aspect of quality, demand availability is understood in this case), in certain cases like the one discussed in this paper, it is subject to optimization as well.

In short:

- modular link capacities are constraints in the optimization problem
- optimum routing is to be found for the traffic demands
- characteristics of the transmission network are to be taken into account

3.2 Availability and protection as a subject to optimization

Protection and availability is an inherent nature of transmission networks. Transmission network designers, and engineers in many cases think that all traffic should be protected. This is very good, from the availability perspective – it provides the well known 99,999% availability for the path.

This might be very good from the technical perspective – on the other hand path protection is an overkill, from the network capacity perspective, whether this is economically viable is up to the service provider to decide. A huge amount of network capacity can be saved by rethinking the current strategy for protecting certain traffic. Eg. it is a viable alternative, to lose some traffic in case of node or link outage from the business perspective, if on the other hand we save a lot of link capacity. Of course this highly depends on customer requirements.

The questions is now what is the acceptable availability (as a measure of demand quality), and how it should be decided what to protect, and what shouldn't.

In order to be able to decide we need to classify the traffic. A certain suggestion will be discussed here, how to do this classification. By no means this is the only possible way of classifying, this is one method, that can be used. In this case, we are considering a multi service provider, that provide voice, and data services, and the majority of the revenue comes from a voice traffic.

We have considered 3 different traffic types for classification:

a. Signalling traffic, signaling does not require too much bandwidth in a typical network however it carries very important traffic. It is a very risky not to protect signalling traffic - with very few business benefits. Signalling traffic should be protected.
b. Voice traffic: This brings most of the revenues for most service providers, however this requires most of the traffic also. A clear decision must be made how much, and what sort of traffic should be protected (Voice Switches are usually configured in load balancing fashion, eg. only part of the traffic is lost, at a single link.). Of course the characteristics of the core voice network need to be taken into account The traffic is to be classified how important it is
c. Data traffic: Data services at the concerning service provider are anyhow only 99,9% availability services. Because of the lower availability requirement in most cases they should not be protected.

Once made that decision, the traffic is to be arranged accordingly.

4 Methods for transmission network optimization

Optimization problems are in general LP/MIP problems. A short introduction to LP in general is discussed in 5.1.. In general Transmission network optimization problems are Mixed-Integer Problems (MIP). (See [1]). Because of this fact they are NP-Complete , which results in the following : solution time increases exponentially with the number of nodes.

It is important to highlight this – and its effect on a real example is to be discussed further in *One practical example*

4.1 Linear Programming (LP), Mixed Integer Programming(MIP)

LP, IP , MIP problems are the subject of Operation research theory, and they formulate problems that needed to be optimized within certain boundaries. According to [2], can be formulated as follows:

LP Problem

indices

j = 1, 2, ..., n variables

i = 1, 2, ...,m constraints

constants

a_{ij} coefficient for variable j in constraint i

b_i right-hand side of constraint i

c_j cost coefficient of variable j

variables

x_j j-th variable

objective

min z = $\sum_j c_j x_j$

constraints:

$$\sum_j a_{ij} x_j \leq b_i$$

$i = 1, 2, ..., m.$

In ordanary words it can be formulated so: we have a vector of variables (x_j), which is with certain weight values (a_{ij}) is bounded by another vector (b_i). These inequalities are the **constraints**. The goal of the problem is to find a feasible variable vector x (eg. an x that fulfills all inequalities), that is optimal. The criterium for optimality is to minimize (or to maximize) a certain function called **objective** function.

If all x_j are real numbers then it is a *linear problem*.

If some x_k of x_j can only be integers, then it is a *Mixed Integer Problem (MIP)*. If all x_j can only be integers then it is *Integer Problem (IP)*.

4.2 Models for transmission network optimization

Three design problems have been taken into consideration, the mixed integer problem (Modular Flow Allocation) uncapacited problems and capacited problems. (See [1] pp. 106-115). These problems are discussed in the following section.

4.2.1 Mixed integer Problem Modular Flow Allocation

"The requirement of integral flow arises naturally when we wish to allocate demand volumes in certain demand modules. For example, in transmission networks, demand volume is usually given in terms of modular units such as the number of Optical careers OC-3s needed between two nodes." (See [1] pp. 123-125)

Its mathematical model is as follows.

MIP: A/MFA

Modular Flow Allocation

constants:

δ_{edp} = 1 if link e belons to path p realizing demand d; 0 otherwise

L_d = demand module for demand d

H_d = volume of demand d expressed as the number of demand modules

h_d = demand volume ($h_d = L_d H_d$)

c_e = capacity of link e

variables:

x_{dp}= flow allocated to path p of demand d (continuous non-negative)

u_{dp}= non-negative integral variable associated with variable x_{dp}

constraints:

$x_{dp}=L_d*u_{dp}$, d = 1,2,…, D ; p=1,2,… P_d.

$$\sum_p x_{dp} = h_d \quad d = 1,2,\ldots, D$$

$$\sum_d \sum_p \delta_{edp} x_{dp} \le c_e \quad e=1,2,\ldots, E$$

Please note that there is no objective function selected for the MIP problem. At this stage this is purposely done so, this will be discussed in Section *Objective function.* In the following 2 sections we have covered two simplification of this problem – in order to get through the NP – Completeness barrier, which significantly limit the number of nodes.

4.2.2 Uncapacited problem – LP – Simple Design Problem

The goal of the uncapacited problem, is to find an optimal solution to the transmission network optimization problem, without the link capacity constraints fixed.

The formulation of the uncapacited simple design problem was the following, that we considered. The mathematical formulation will be as follows (See [1] pp 108-110):

LP:D/SDP : Simple Design Problem

indices

d=1,2, … D demands

e=1,2,… E edges /arcs/links

v=1,2,...V nodes, vertices

constants:

a_{ev} = 1 if link e originates at node v; 0 otherwise

b_{ev} = 1 if link e terminates at node v; 0 otherwise

s_d = source node of demand d

t_d = sink node of demand d

h_d = volume of demand d

ξ_e = unit cost of link e

variables:

x_{ed} = flow realizing demand d allocated to link e (continuous non-negative)

y_e = capacity of link e (continuous non-negative)

objective:

minimize $F = \sum_e \xi_e y_e$

constraints:

$\sum_e a_{ev} x_{ed} - \sum_e b_{ev} x_{ed}$ =

= a. h_d = if v= s_d

b. 0 if v<> s_d , t_d v=1,2…V d=1,2…D

c. -h_d = if v= t_d

$\sum_d x_{ed} \leq y_e$ e=1,2,….,E

Please note that in this particular case there is an objective function. This is due to the fact that there is no capacity limit imposed on the links (or the capacity limits are also variables).

4.2.3 The capacited problem – LP- Pure Allocation Problem

The capacited problem, is basically the Linear variant of the MIP, without the modular nature of transmission network.

The formulation of the problem we considered for the transmission is the following:

LP:A/PAP: Pure Allocation Problem

constants:

δ_{edp} = 1 if link e belons to path p realizing demand d; 0 otherwise

h_d = volume of demand d

c_e = capacity of link e

variables:

x_{dp}= flow allocated to path p of demand d (continuous non-negative)

$\sum_p x_{dp} = h_d$ d = 1,2,…, D

$\sum_d \sum_p \delta_{edp} x_{dp} \leq c_e$ e=1,2,…, E

Please note two things. 1, objective functions is not selected, and 2 the similarities, and the key differences with *Mixed integer Problem Modular Flow Allocation*

4.2.4 Objective function

So far we have not selected an objective function. The selection of an objective function in itself can be a challenging task. The literature (See [3] pp. 114] referred to in this book, suggests an objective function:

minimize $F = \sum_d \sum_p \rho_{dp} x_{dp}$

where $\rho_{dp} = \sum_e r_e \delta_{edp}$ is the unit revenue from path P_{dp} of demand d in terms of link revenue r_e .

However this is by far not the only objective function that can be used, but a well usuable one. So we will use a modification this (the sum of all number of hops of all demands).

4.3 Simplifying the network

As the number of nodes in the real life problem is several hundreds it is important to think over what sort of modifications of the network can be used. A few of these modifications are:

a. removal of non-sink and non-source nodes with exactly 2 edges. (These are the so called boosters or repeaters) or 2 degree nodes
b. aggregating of some sources and demands into a supernode aggregating sources and demands.

They have a drawback also : the interconnection traffic might not be correctly calculated between such nodes.

In our network a simplification of a different kind has been used:

a. the nodes at each site have been merged into a supernode (see figure)

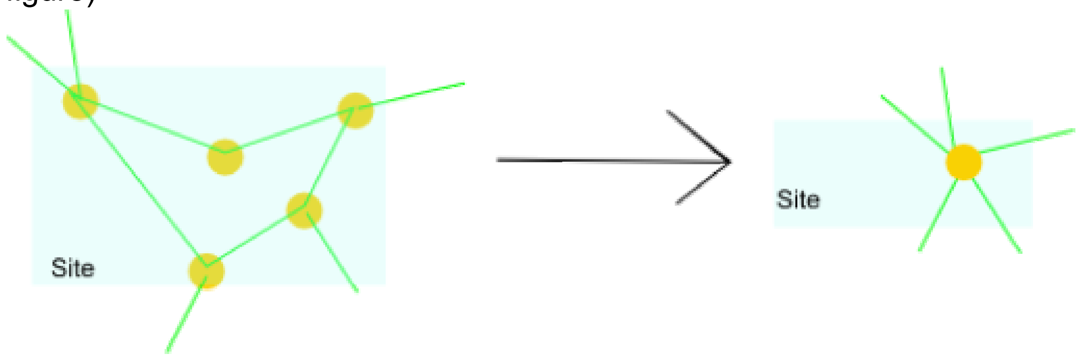

Figure 1

b. the trivial links have been removed (see figure)

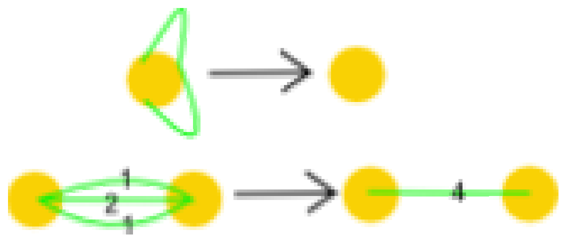

Figure 2

c. we substituted the n parallel links with one link with the sum of the original capacities (see figure)

5 One practical example

The following chapter deals with the practical results of an optimization project. Our goal in this chapter is to show that optimization techniques are beneficial to network operators. The measure that we are going to take into consideration is the comparison of the network to a optimum stage, where the link capacities (according to our objective function) are at a minimum level, while fulfilling the demand, and link capacity constraints.

The quality measure that we used in the network to present the quality is the average length of the paths – as they are somehow in connection with link capacities. This quality measure is a general unit for measurement, by no means the only possible measurement unit, however – as our figures will show, it gives an easy comparison for the results.

5.1 Introduction of the example network

The transmission network itself is divided into 4 optical rings(thick lines) and 6 microwave radio rings (thin lines), the access network consists of PDH trees (in which there are no chances for optimization – as there is always one path from the nodes to the boundary of the SDH transmission network).

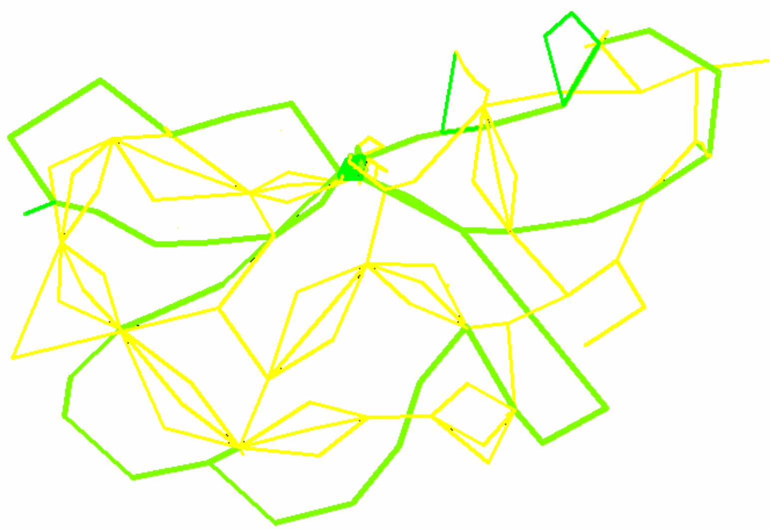

Figure 3

5.2 Initial results

We followed the process described in Phases of a network optimization project for reaching the practical results.

After finishing Phase I and II (referring to *Phases of a network optimization project* chapter here) we have figured out that because of the network evolution over time, the actual network is predicted to be far from optimal.

In Phase I, we created a statistics of the network with the current demands, showing the actual path lengths in terms of edge/link sections.

Eg. there were trails in the network that were using up too much capacities, and containing too many hops.

Such typical trails are depicted on the following figures:

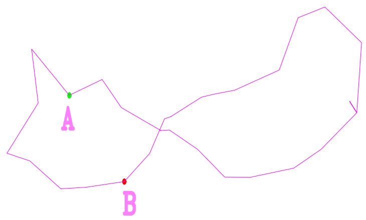

Figure 4

A trail from A to B is directly connected, however its protection trail travels through an extra ring (at the right-hand side).

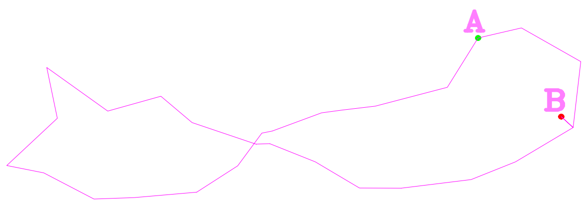

Figure 5

A similar trail from A to B is directly connected, its protection trail goes trough ring in the left-hand side. An even more extreme example:

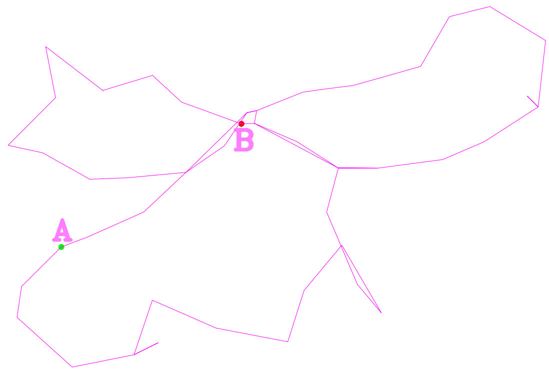

Figure 6

The trail from A to B travels through all the optical rings.

The other major discovery of Phase I was that the network is flat – eg. not divided into hierarchies. All traffic demands are handles as equal.

The two main characteristics we identified were:

- flat topology
- trail lengths are long

5.3 Feasibility study

In Phase II, we tried to do an estimation for optimum. For this we used a method of finding the shortest paths or trails for a certain traffic demand. We considered 4 cases for this:

1. Uncapacited links, shortest paths – in this case we considered unlimited capacities on the network links, and we used the method of shortest paths (Dijkstra algorithm, [2]) for finding the shortest paths for a demand
2. Capacited shortest paths – in this case we took the link capacities into consideration, and we still used the Dijkstra shortest path algorithm for a given demand
3. Protected demands, uncapacited links shortest paths. In this case we took protection of demands into consideration (eg, for the protection path for a demand we removed all the nodes and links of the active path except for the start and end node) (The protection and active paths were link and node disjoint).
4. Like in case 3 we took protection into consideration but this time with capacity constraint on the links

Our findings after Phase 2 is summarized in the following table:

	current situation	Uncapacited links	uncapacited with protection	capacited	capacited with protection
# of edges	%	%	%	%	%
1-10	85.26	98.16	98.16	97.28	95.53
1-5	***65.40***	***78.40***	***78.42***	***77.58***	***78.57***
6-10	***19.86***	***19.76***	***19.74***	***19.70***	***16.97***
11-20	11.14	1.84	1.84	2.72	4.45
21-30	1.26	0.00	0.00	0.00	0.02
>31	0.80	0.00	0.00	0.00	0.00
average:	**5.50**	**3.75**	**3.75**	**3.81**	**3.83**

Table 1

Taking into account that the methods used here do not provide in every case a global optimum, they provide only near-optimum situation state we an average of 30% saving is estimated in capacities after the actual Optimization.(Phase III).This is estimated from the figures that the average hop count went down from 5.5 to 3.83.

5.4 Optimization - Finding the global optimum

5.4.1 Simplifying the problem

The actual network to be optimized consists of 251 nodes, 399 edges/links, and 3874 2Mbit/s demands. In order to find a global optimum, the *Mixed integer Problem Modular Flow Allocation* should be solved. But due to the fact that the problem is a MIP problem, and therefore it is NP complete (See Linear Programming (LP), Mixed Integer Programming(MIP)). NP – completeness means in practice, that the number of nodes determine the solution time, and the solution time grows exponentally with the number of nodes.

Therefore this is far too big problem for a MIP problem solver, so the problem had to be simplified. The methods for simplification have been discussed in section Simplifying the network

After making the simplifications, the network dimensions have dramatically decreased:

- The number of simplified nodes went down to126
- The number of simplified edges went down to 173
- The number of simplified demands went down to 342

This is a much smaller problem in size, but unfortunately it still can not be solved if it is an MIP problem. Therefore we used a further simplification – in order to reach practical results on time.

As the problem still can not be solved if the Mixed integer Problem Modular Flow Allocation model is used, we need to consider an LP problem. This can easily result in a situation, that we haven't found the actual optimal solution of the original problem, but we are going to find a solution close enough to the optimum, which is acceptable.

5.4.2 Formulating of the LP problem

The formulation of the LP problem is not trivial. The mathematical definition of the problem is described in Section (The capacited problem – LP- Pure Allocation Problem). Formulation of the LP problem consists of the following steps:

- Formulating the constraints for the problem(demand and edge constraints)
- Formulating the objective function

After the formulation the problem can be solved with an LP Solver like "LP_Solve". Our purpose in the following part of the paper is to generate an example file, with constraints and an objective function which can be used as an input for LP_Solve.

So first the constraints must be defined, we start it by defining the so called demand constraints.

A *demand constraints* looks like this in its formulation:

D204375734425243631651958: +C91 +C92 +C93 +C94 +C95 +C96 +C97 +C98 +C99 +C100 = 62720; [6.4.2. a]

Dxxx, is an abbreviation for a certain demand. Each demand is uniquely generated from a summarized traffic demand with its source and destination (using topological information). Cxxx are variables, each variable represent a demand-path pair (each demand has a set of candidate paths). This is the so called link-path formulation[1].

A demand constraint represents that the actual traffic demand in bit/s from Node A to Node B, must be equal to its actual value, no matter which path we choose (eg. irrelevant of the actual value of the Cxxx variable). This is shown in the above example (the sum of the variables equals the total demand.)

An *edge constraint* looks like this in the LP problem definition:

E085250584720080700628900: +C433 +C542 +C543 +C1041 +C1252 +C1253 +C2172 +C2173 +C2631 +C2873 +C2874 +C3055 <= 186624; [6.4.2.b]

The Exxx denote the link or edge constraint, Cxxxx denote the path variables in the function. This constraint represents that the link flow must not be over the capacity of the link.

The selection of the *objective function* – or the goal to which we want to optimize is an important task. In this case we used the sum of the link flows as an objective function in order to minimize link flows – or to maximize link capacities.

Such a line looks like this in the LP formulation:

min +2 C1 +3 C2 +3 C3 +3 C4 +3 C5 +… +4 C8548 +4 C8549 +4 C8550 [6.4.2c]

The min shows that we are looking for the minimum of the function, and the sum of the link flow variables is the function to be optimized.

The LP formulation consists of therefore:

- demands constraints [6.4.2a]
- edge constraints [6.4.2b]
- objective function [6.4.2c]

The LP problem in an LP_Solve formulation consists of over 3000 lines and it includes over 8550 variables in a typical case(the number of the variables depends on the number of paths for each demand, and the number of demands).

The typical calculation time for such a problem on a Celeron M 800 Mhz, is 25 paths is approximately 1 minute.

The following table shows the actual calculation times in terms of the depth of the path finding, and the number of paths.

Description	**Runtime [sec]**	**Depth of Path finding**	**Number of Paths**	**Number of variables**
Path finding 1.	66.50	20	25	8550
Path finding 2.	71.50	20	10	3420
Path finding 3.	272.894	25	100	34200
LP solution time 1.	3.185	20	25	8550
LP solution time 2.	1.45	20	10	3420
LP solution time 3.	18.5	25	100	34200
Total time 1.	70.2	20	25	8550
Total time 2.	74.3	20	10	3420
Total time 3.	297.099	25	100	34200

Table 2

5.4.3 Results of the optimization

The optimization resulted in a set of paths for all demands that is the optimum of the LP problem, this we do not want to include here due to size limitations. Interestingly enough, in most cases the optimum path was the shortest possible path, this was due to the fact that there were enough free capacities in the network.

If there are enough free capacities in the network the shortest path algorithm gives a good estimate. However if the free capacities are getting less, there might be a situation where because of the lack of free capacities the shortest path calculated one by one (each path calculated independently, one after another) could result in situation in which the path calculated later, must be a long path (as the free capacities have been utilized) . In this case the overall paths might be longer than in a situation where the calculation for the paths is based on variables effecting the whole network.

Since there was enough free capacity in the network our first estimation in Phase II was close to the actual optimum.

It is important to cover in this Section as well the potential errors, that may have occurred:

- The LP problem formulation we covered so far, has not dealt with the problem of protection paths, but in practice we have to cover this problem as well. This is not discussed in this paper
- The optimum of the LP problem might not be the optimum of the original problem. For this, we need to find an estimate, how acceptable our solution is, and what percentage is it better than the original. If it is close to the optimum of the original problem, the LP solution is acceptable.
- Currently we are in this phase (3), and we have not yet reached re-routing, and final conclusion drawing – it might be that we are going to find some of the errors that we have made in a latter phase.

Based on the following assumptions we made several simulations with several cases changing the edge capacities. At 100 % capacities the results were exactly 3.75 as with Dijkstra. At 70 % capacities the results were approximately 3.8, slightly better than Dijkstra. At 50%, 40% capacities, there were no solution with Dijkstra, only with the LP calculation method.

To summarize the results optimum solution with 100% utilization is based on the Dijkstra algorithm.

6 Summary

Our intention with this paper was to give a systematic overview of network optimization, and to introduce some methods we have used in a live network.

In this paper we have covered:

- A systematic approach and project phases for a network optimization project in Chapter : *Phases of a network optimization project*
- Characteristics of a transmission network traffic optimization project in Chapter *Transmission network traffic optimization*
- Mathematical methods for transmission network traffic optimization in *Methods for transmission network optimization*
- Results based on this methodology in a live network in One practical example

In Chapter 5 we tried to show that using well built mathematical models for optimization results in an optimum network in terms of link capacity.

This has brought up to 30% better utilization in the given network, which results in cost savings mostly in CAPEX, and with in case it is used well it can help network designers in finding free capacities in the network – which helps network designers when planning future extensions and investments.

In short, using this methodology a set of tools can be built up for the transmission network designers, that enable them to use their own network resources in a more efficient way. An even better performance can be achieved by applying automatic methods for rerouting.

7 List of acronyms

CAPEX – Capital Expenditure

D.A.R.P.A - Defense Advanced Research Projects Agency

C.O.R.O.N.E.T - Dynamic Multi-Terabit Core Optical Networks: Architecture, Protocols, Control and Management

RFQ – Request for Quotation

IP – Internet Protocol

ATM – Asynchronous Transfer Mode

MPLS – Multiprotocol Label Switching

QoS – Quality of Service

LP – Linear Programming

MIP – Mixed Integer Programming

NP - non-deterministic polynomial time

SDP – Simple Design problem

PDH - Plesychronous Digital Hierarchy

SDH – Synchronous Digital Hierarchy

8 Bibliography

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[1] M. Pióro, D. Medhi: Routing Flow and Capacity Design in Communication Networks, Morgan and Kaufman, June 2004. [pp. 625-638]

[2] Pióro, Medhi: Routing Flow and Capacity Design in Communication Networks [pp. 153-154]

[3]Pióro, Medhi: Routing Flow and Capacity Design in Communication Networks [pp.114]

[4] Planning reliable UMTS terrestrial access networks :Szlovencsak, A. Godor, I. Harmatos, J. Cinkler, T. Ericsson Res.;Communications Magazine, IEEE, Jan 2002 Volume: 40, Issue: 1 [pp66-72]

[5] Kommunikációs hálózatok költséghatékony tervezése a forgalomeloszlás periodikus változásainak figyelembevételével ,

Tamási Levente, Józsa Balázs Gábor, Orincsay Dániel, Híradástechnika 2004

[6] Stalled information based routing in multidomain multilayer networks Szigeti, J. Tapolcai, J. Cinkler, T. Henk, T. Sallai, G. Telecommunications Network Strategy and Planning Symposium. NETWORKS 2004, 11th International pp[297- 302]
[7] Kommunikációs hálózatok költséghatékony tervezése Orincsay Dániel és Józsa Balázs Gábor, Híradástechnika 2003